

GPS on International Space Station (ISS) and Crew Return Vehicle (CRV)

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ABSTRACT

Both the International Space Station and Crew Return Vehicle desired to have GPS on their vehicles due to improve state determination over traditional ground tracking techniques used in the past for space vehicles. Both also opted to use GPS for attitude determination to save the expense of a star tracker. Both vehicles have stringent pointing requirements for roll, pitch, and heading, making a sun or earth sensor not a viable option since the heading is undetermined. This paper discusses the technical challenges associated with the implementation of GPS on both of these vehicles. ISS and CRV use the same GPS receiver, but have faced different challenges since the mission of each is different. ISS will be discussed first, then CRV. The flight experiments flown on the Space Shuttle in support of these efforts is also discussed.

BACKGROUND

The ISS is planning to use a GPS receiver to provide position, velocity, time reference, and determine attitude. ISS uses the GPS position and velocity solution as the ISS navigation state. The ISS's attitude determination filter combines the GPS receiver attitude information with ring laser gyro data available from the ISS rate gyro assembly (RGA) to produce the ISS attitude solution. ISS has 2 GPS receivers that are installed in the ISS now. The GPS antennas are due to be installed on the ISS in April, 2002, at which point, the ISS GPS capability becomes operational. The ISS GPS receivers are supposed to be operational for a minimum of 10 years.

The CRV is planning on using GPS to aid a filter residing inside the CRV navigation sensor that combines the GPS position, velocity, and attitude solution with rate gyro and accelerometer data to output position, velocity, and attitude. Each CRV will be refurbished every 2 to 3 years.

TECHNICAL CHALLENGES FACING BOTH CRV AND ISS

One of the main technical challenges that faced both ISS and CRV were that there existed no space rated GPS attitude capable receiver that outputs data in the required Mil-Std 1553 format. For vehicles such as ISS and CRV that contain many different components, Mil-Std 1553 is required to make communication with a variety of boxes possible. In order to minimize the design impacts to current off the shelf receivers, a traditional serial interface receiver was integrated into a Space Integrated Global Positioning System/ Inertial Navigation System (SIGI) which could provide the 1553 interface.

Also, the international partners objected to the use of the military GPS frequency, and required that the ISS/CRV receiver be L1 only. These decisions were being made when Selective Availability (SA) was still active, so the receiver would be subject to the degraded performance caused by (SA). Now that SA has been turned off, the design changes implemented to filter the GPS position and velocity solution to meet the ISS state vector requirements are no longer needed, and the ISS is using the state vector solution directly from the GPS receiver as the ISS state. ISS does have a filter to propagate the state during outages, but that filter resided in the ISS software, not in the GPS receiver or the SIGI software. The CRV state is filtered by combining gyro data with the GPS raw measurements within the SIGI to create a state that meets the CRV requirements. The CRV state was required at 50 Hz, which can be provided by the filtered state, whereas the GPS only state is output at 1 Hz.

TECHNICAL CHALLENGES UNIQUE TO ISS

The major challenges for putting GPS on ISS were the rich multipath environment, 100 foot cable runs that would be mated for the first time during the ISS assembly sequence, and the changing attitude orientations of the ISS. Each of these challenges will be addressed. These challenges affect the attitude determination capability of the receiver much more than the position, velocity capability of the receiver. The theory and equations to use GPS differential carrier phase measurements for attitude are developed in [Ref 1].

Multipath

Figure 1 shows the ISS and the GPS antenna locations, and Figure 2 shows an expanded view of the GPS antennas on the S0 truss.

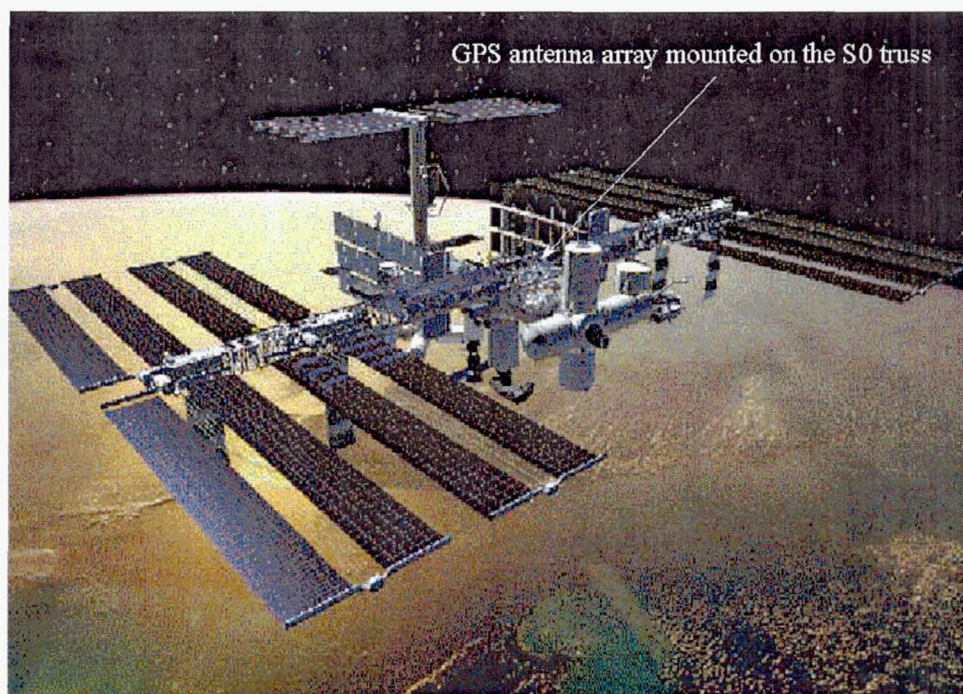


Figure 1 – ISS at Assembly Complete

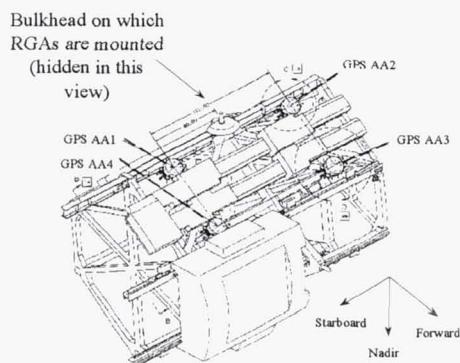


Figure 2 - Expanded View of GPS Antennas on the S0 Truss

The ISS antennas are arranged in a 1.5 m by 3 m rectangle. The antenna configuration was selected so that the antennas were far enough apart that a more precise attitude could be determined, but close enough together that integer resolution using a search technique was possible.

The ISS is made up of many large reflective objects. These large objects, such as the solar panels, cause multipath. The amount of distortion the multipath was going to cause needed to be determined before GPS went operational on ISS. Unfortunately, since ISS is assembled in space, there existed no opportunities to determine the how badly the multipath was

going to affect the GPS by simply collecting data on the real vehicle. The affect of the multipath had to be calculated. To calculate the multipath, a Geometric Theory of Diffraction (GTD) code was used. The GTD code [Ref 2] had been used to determine multipath affects on the gain of RF signals for Space Shuttle work, but had never been used to determine phase offsets. Therefore, a series of ground tests to verify that the code would correctly calculate phase as well as gain changes caused by multipath was undertaken. The ground tests consisted of taking large reflective objects into the field and using a GPS receiver to measure the change in phase the resulted from the reflective objects. The measured data was then compared to the GTD predicted phases, as reported in [Ref 3]. Figure 3 shows a picture of one of the reflective objects in relation to the antennas used in the field testing. The same GTD code was used to compare GPS data collected during a shuttle flight experiment during STS 77 in May 1996 [Ref 4]. In both cases, the GTD code matched the GPS receiver well enough for NASA, and the independent assessment team that was formed to independently assess the risk multipath posed for GPS on ISS, to consider the GTD code as verified and acceptable to use to determine the multipath effects on ISS. To determine the differential carrier phase errors for both the field test and the shuttle flight experiment, the measured differential carrier phase errors from the GPS receiver were subtracted from the true differential carrier phase. The true differential carrier phase was calculated using the true attitude, which for the field test was measured using star sightings, and for the shuttle flight experiment the shuttle's attitude was used as truth. The shuttle's attitude is derived from star tracker measurements and precise gyro measurements. Figure 4 shows the payload bay arrangement during STS 77 flown in May 1996. The 4 GPS antennas were arranged in a 1.5 m by 3 m rectangle to simulate the ISS GPS antenna configuration. [Ref 3] and [Ref 4] contain more details of the data reduction methods used for the field test and for the shuttle flight experiment.



Figure 3 Field Test Multipath Object and GPS Antennas

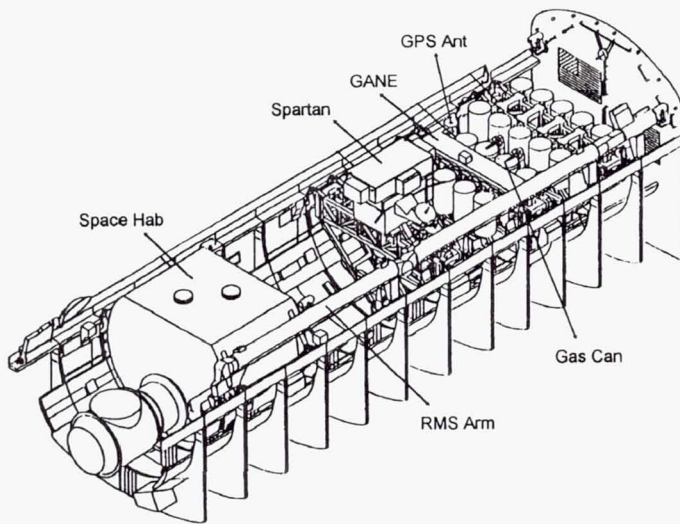


Figure 4 – Payload Bay Arrangement During STS 77

Figure 5 is a sample of the GTD predicted phase errors compared to the measured phase errors for data collected during STS 77.

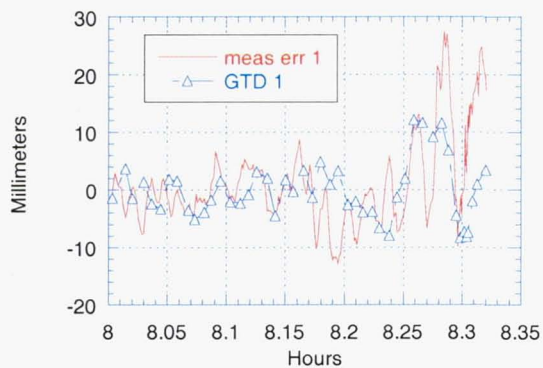


Figure 5 – Measured Differential Carrier Phase Errors Compared to GTD Predicted Differential Carrier Phase Errors for SV24 and Antennas 1 and 2

The GTD code was then used to determine the multipath environment for different assembly phases of the ISS. These predictions were used as inputs in the various simulations of GPS on ISS, including the hardware in the loop simulations that use a Development Test Unit (DVTU) of the ISS GPS receiver in conjunction with a GPS signal generator. Figure 6 shows the GTD predicted phase errors for Antenna 1 for ISS at assembly complete. Since the solar panels rotate, the multipath environment is always changing. To be conservative, the worst solar panel orientation was used. Multipath mitigation techniques, such as spherical harmonic curve fits [Ref 5], were considered; but the added complication of the changing ISS configuration and the moving solar panels made such techniques implausible. Instead, it was decided to use choke ring type antennas to help mitigate multipath.

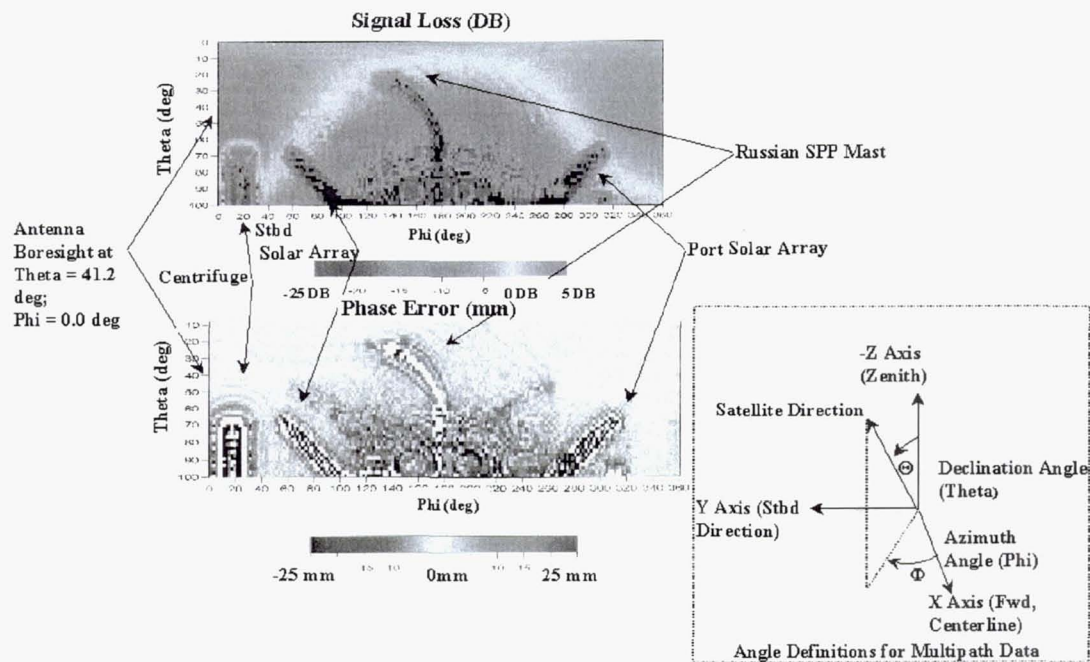


Figure 6 – Carrier Phase Errors for Antenna 1 on ISS at Assembly Complete

Figure 7 shows typical GPS attitude performance for the ISS for the assembly complete configuration. The data was generated from a DVTU ISS/CRV GPS receiver on a GPS RF signal generator.

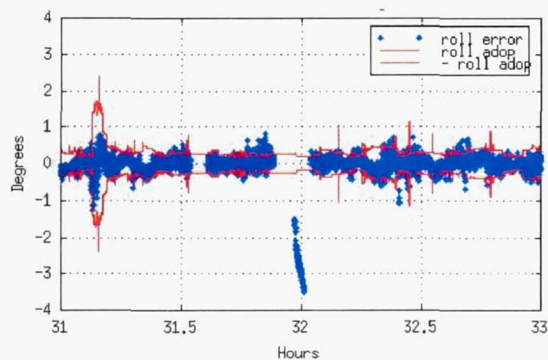


Figure 7 – GPS Attitude Roll Error and Roll ADOP.

The ADOP is formulated in [Ref 1] and is an indication of the accuracy of the GPS attitude solution. Notice that multipath can cause large errors, such as those seen at hour 32, that are not tracked by ADOP since ADOP does not have any knowledge of the multipath. The GPS attitude solution is not accurate enough to meet the ISS requirement. A filter in the ISS combines the GPS attitude data with rate gyro data from a Rate Gyro Assembly (RGA) on the ISS to produce an ISS attitude that meets the ISS 0.5 degree requirement. [Ref 6] describes the ISS filter and shows accuracy results from simulation testing.

100+ Foot Cable Runs That Don't Mate PreFlight

One major difference between ISS and GPS attitude on airplanes or ships is that ISS has 100+ cable lengths that do not mate preflight. Many attitude algorithms calibrate the bias on the differential carrier phase measurements by measuring the cable

lengths. Some receivers have software to automatically determine these path lengths using a static 'self survey.' However, ISS could not use this technique since its cables don't mate preflight. Additionally, the changing thermal environment causes the cables to change length, which changes the electrical path length, which can cause biases in an attitude solution. In the multipath field test, attitude biases of up to 0.5 degrees were observed in the single difference attitude solution, whereas the double difference solution did not show the biases, but was noisier as the theory predicted. ISS opted to use the double difference. [Ref 1] develops the equations for using GPS differential carrier measurements for single or double difference measurements. [Ref 8] shows the results of using both single and double difference measurements.

Variable Attitude Orientations

Another challenge for ISS was the changing attitude orientations. Most satellites are spin stabilized and are zenith pointing. ISS changes attitudes from sun pointing for solar panel pointing, to LVLH for when shuttle is docked, to inertial hold for soyuz docking. An input was added to the receiver to tell it what part of the sky to look for satellites in.

ISS Flight Experiments

In order mitigate the risk associated with using GPS on ISS, 2 flight experiments were flown with the ISS/CRV GPS receiver on the Space Shuttle, in STS 101 and STS106. The same platform that was flown in STS 77 was again flown, but with an actual ISS/CRV GPS receiver flight unit. Two star trackers were flown as independent attitude truth sources, and an L1/L2 keyed GPS receiver was used for position, velocity comparison. Figure 7 shows the GPS antennas mounted on the structure in the payload bay for STS 106.

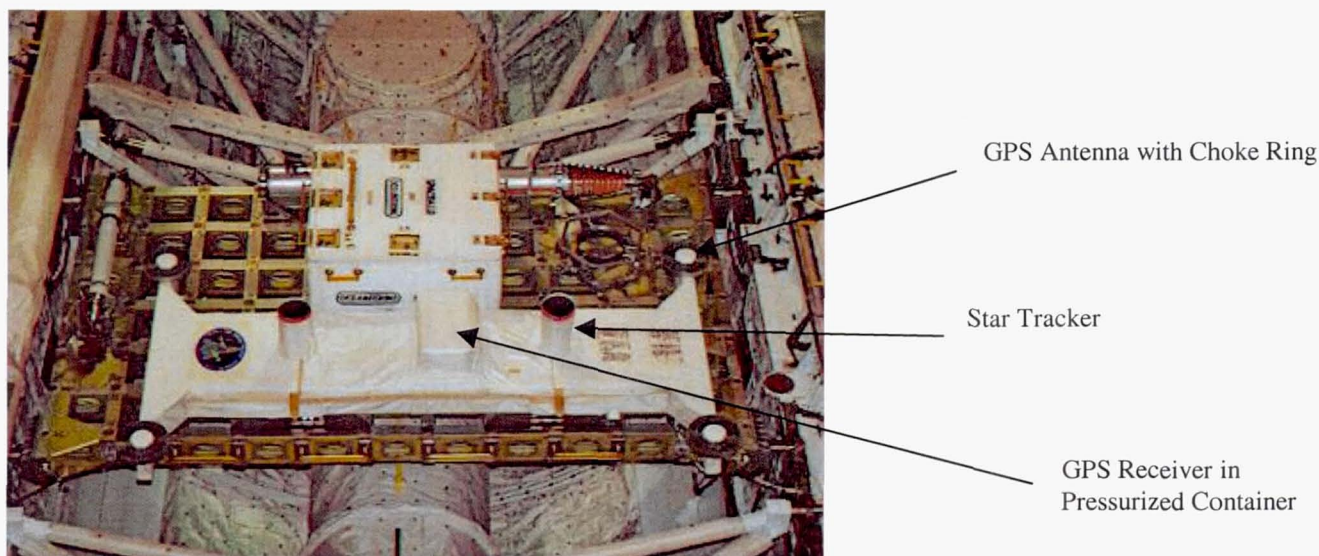


Figure 8 GPS Antenna and Structure in Payload Bay for STS 101 and STS 106

Figures 9, 10, and 11 show position and attitude errors during STS 101 for a period of time when the orbiter was flying in an attitude that mimics the attitude the antennas on ISS will be in. Results from STS 106 were similar.

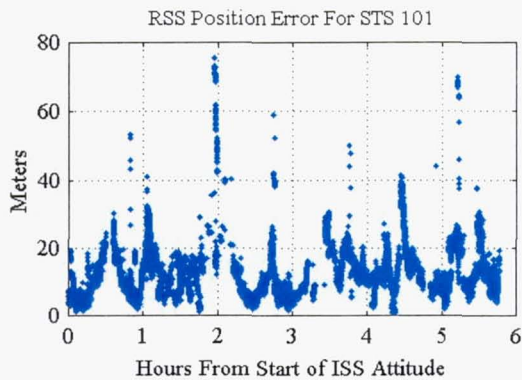


Figure 9 RSS Position Error During STS 101

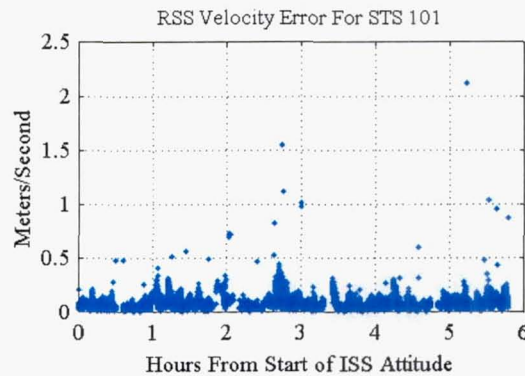


Figure 10 – RSS Velocity Error During STS 101

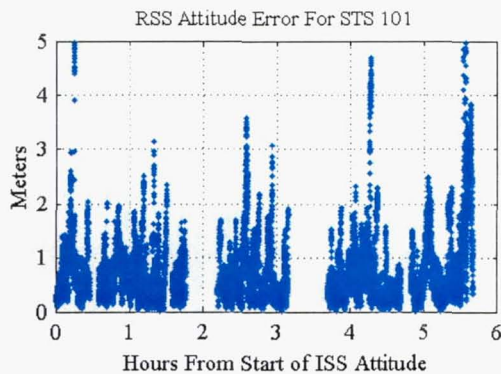


Figure 11 – RSS Attitude Error During STS 101

CHALLENGES UNIQUE TO CRV

The major challenges that are unique to CRV are a result of CRV reentering the atmosphere. The GPS receiver has to go through the region referred to as the blackout region where RF signals encounter a lot of disturbance due to the Earth's ionosphere. The RF signals received are a much lower signal strength, and typically GPS tracking is reduced to less than 4 satellites for several minutes. The GPS receiver needs to be able to reacquire the GPS signal following blackout. However, it is difficult for the GPS receiver to propagate its position during the blackout region since it is no longer in an orbital trajectory, but dead reckoning is not a very precise fit to the trajectory either. As of date, 2 flight experiments have been flown on STS100 and STS108 where the GPS receiver for CRV was powered and collecting data during the entire de-orbit and landing of the shuttle. During STS 100, the GPS receiver was not aided, and it dead reckoned through the blackout region. The blackout region for shuttle starts at around 270,000 feet and ends around 220,000 feet. During STS100, the GPS receiving started dropping satellites at 270,000 feet, dropped below 4 at 240,000 feet, and didn't reacquire until 130,000 feet for a total time without 4 satellites of 16 minutes. For comparison, a different GPS receiver slated for Shuttle that is L1/L2, keyed, and aided by the shuttle's inertial state, experienced a total time with less than 4 satellites of less than 1 minute. During STS 108, the CRV GPS receiver started dropping satellites at 270,000 feet, again dropping below 4 at 240,000 feet, but was inertially aided, and recovered at 210,000 feet for a total time with less than 4 satellites of 6 minutes. Figures 13, 14, 15 and 16 show the position and velocity errors of the CRV GPS receiver as compared to the Shuttle GPS receiver during the reentry for STS 100 and STS 108.

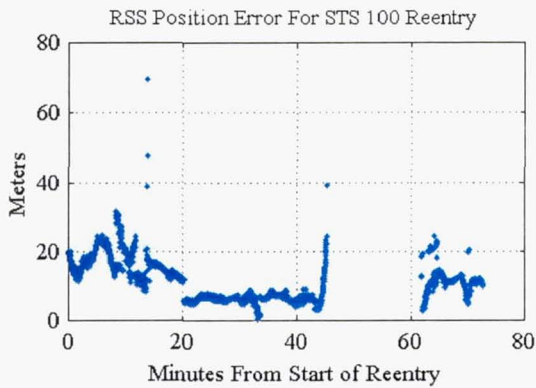


Figure 13 RSS Position Error for STS 100

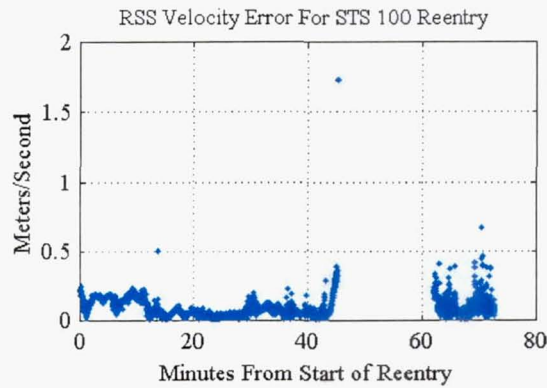


Figure 14 RSS Velocity Error for STS 100

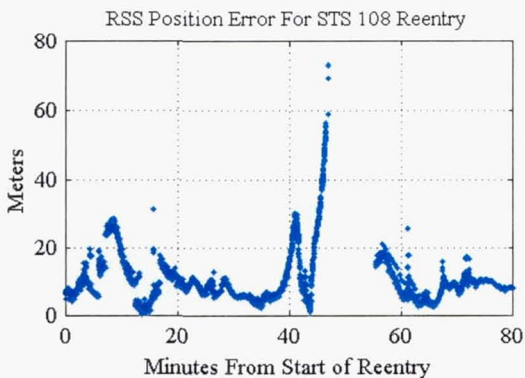


Figure 15 RSS Position Error for STS 108

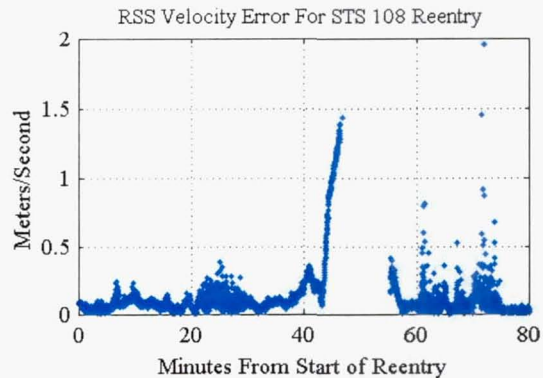


Figure 16 RSS Velocity Error for STS 108

The other requirement unique to CRV was the ability for the receiver to be able to acquire attitude with no prior attitude knowledge. Many GPS receivers requires an attitude guess to aid in integer resolution. An attitude scheme using the signal strength data from a single antenna to provide an initial attitude guess was added and tested in the STS 106 flight experiment. The additional algorithm added less than 1 minute to the time to acquire attitude. [Ref 7] has more information on using the signal strength to determine a course attitude.

MANUFACTURERS

The GPS receiver for ISS and CRV is a Trimble Force 19. It is packaged inside a Honeywell Space Integrated Global Positioning System /Inertial Navigation System (SIGI). The ISS Rate Gyro Assembly is also manufactured by Honeywell. The GPS antennas for ISS are Dorne Margollen antennas housed in a NASA built choke ring assembly. The antennas for CRV are NASA built patch antennas. The GPS receiver used in the STS 77 flight experiment was a Trimble TANS Vector. The GPS receivers used for the multipath field test were a Trimble TANS Vector and Trimble TANS Quadrex. The antennas flown on STS 101 and STS 106 flight experiments were MicroPulse choke ring antennas. The RF signal generator used in ground testing is a Spirent 4 RF GPS signal generator. The GPS receiver slated for the Shuttle is the Miniature GPS Receiver (MAGR) manufactured by Collins.

REFERENCES

- [1] Gomez, Susan F., 'Attitude Determination and Attitude Dilution of Precision (ADOP) Results for International Space Station Global Positioning System (GPS) Receiver,' *Proceedings of the National Technical Meeting*, The Institute of Navigation, Sept. 2000.

- [2] Marhefka, R. J., and J. W. Silvestro, 'Near Zone Basic Scattering Code User's Manual with Space Station Applications,' NASA Contractor Report 181944, ElectroScience Laboratory, Ohio State University, December 1989.
- [3] Gomez, Susan F., et al., 'Evaluation of Two Computational Techniques of Calculating Multipath Using Global Positioning System Carrier Phase Measurements,' NASA Technical Memorandum 104816, April 1996.
- [4] Gomez, Susan F. and Shian Hwu, 'Comparison of Space Shuttle GPS Flight Data to Geometric Theory of Diffraction Predictions,' *Proceedings of the National Technical Meeting*, The Institute of Navigation, Jan 1997.
- [6] Treder, Alfred J., Pendergrass, James R. and Gomez, Susan F., 'GPS-Updated Attitude Determination Performance on ISS Despite Rich Multipath' *AIAA Guidance, Navigation, and Control Conference*, 200.
- [5] Cohen, Clark E., 'Attitude Determination Using GPS,' Stanford PhD Thesis, December 1992
- [6] Gomez, Susan F., 'Field Test Comparison of Static GPS Attitude Determination Using Single and Double Difference Carrier Phase Measurements' NASA JSC Memorandum EG-95-006, March, 1995.
- [7] Um, Jaeyong, 'Relative Navigation and Attitude Determination Using a GPS/INS Integrated System Near the International Space Station,' Ph.D. Dissertation, The University of Texas at Austin, December 2001.

ACKNOWLEDGEMENTS

Development of the CRV and ISS SIGI has been a team effort between NASA Johnson Space Center, NASA Goddard Space Flight Center, Honeywell, and Trimble. Honeywell built the SIGI, and integrated the GPS receiver into the SIGI. Greg McFerren provided valuable ISS SIGI support, and a newly formed HI CRV SIGI team, including Greg McFerren, Tiffany Nesbit, Criag Allen, Tom Campbell, Dan Bobcinski, Jeff Ring, Andy Guyette, Ryan Parry, and Jeff Hegg is providing further development of CRV SIGI. The team at Trimble, including Paul Turney, Paul Braisted, Robert Abad, and John Kahle, has provided superb support for both the ISS and CRV developments of the Force 19 GPS receiver. Glenn Lightsey is responsible for the attitude coding of the receiver, and Chip Campbell and Jim Simpson of NASA provided valuable coding and testing of the attitude code in the GPS receiver. NASA support, including Greg Blackburn, Aaron van Baalen, Kevin Dunn, David Saley, Tim Woeste, Mike Ruiz, Jody Yeo, Tony Pham, Moi Montez, Jenny Wagenknecht, John Muratore, and Penny Saunders provided valuable testing, analysis, documentation, integration and support for the GPS on ISS and the SIGI project. Lockheed and Boeing support for the flight experiments, including Ken Vorhaben, Cary Semar and Einar Thorsen, was very valuable. The GPS multipath analysis was provided by Bob Panneton of NASA, and Shian Hwu, and Ba Lu of Lockheed. Link margin and coverage analysis of ISS was provided by Laura Hood and Cathy Sham of NASA, and Antha Adkins of Lockheed. Boeing, including Jeff Patterson, Roger Corson, Jim Pendergrass, and Al Treder of Dynacs, wrote firmware for ISS that eased integration of SIGI into ISS and provided valuable analysis of the results of combining the SIGI and RGA data in the ISS filter.

BIOGRAPHY

Susan F. Gomez received her B.S. from the University of Texas in 1992. She has been working at NASA-JSC on navigation and attitude determination for ISS and CRV since 1993. Currently her job titles are ISS SIGI Technical Lead and CRV SIGI Project Manager.